EXPERIMENTAL STUDY OF DEFORMATION OF IGNEOUS ROCKS AT HIGH TEMPERATURE AND PRESSURE

BY

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1. Introduction

We studied in the early papers the experimental deformation of igneous rocks under high confining pressure,[3] and we also estimated the strength distribution in the earth's crust and the upper mantle by use of the above results and made reference to the occurrence of the large scale earthquakes.[4]

It is well known that the earth's interior is under the condition of very high temperature, concurrently under high pressure. The effect of temperature on the mechanical properties of rocks is extremely large, then the experimental results of rock deformation at high temperature will be a very important factor for the study of various geophysical problems.

It is generally accepted that the temperature of the earth's interior is; 0–600°C in the continental crust, 0–300°C in the ocean floor, 300–1000°C in the upper mantle, and approximately 1500°C at the depth of 100 km. We have to study the effect of temperature on the physical and chemical properties of igneous rocks at least up to 800–1000°C, and if possible, up to 1500°C or more. This temperature range will cover sufficiently the temperature condition in the earth's crust and outermost layer of the mantle.

As the introductory study of this project, we studied the effect of temperature on the stress-strain relation, the strength and the elastic constants of the igneous rocks at various confining pressures.

Each specimens were deformed by the statically applied axial compressional force at 1 bar and various confining pressures.

All the specimens used in this series of experiments were shaped in column. The specimens used in the high temperature experiments were Kitashirakawa biotite granite, 3 cm in diameter and 6 cm in length, and Yakuno olivine basalt, 2 cm in diameter and 4 cm in length. The specimens used in the experiments at high temperature combined high pressure were Kitashirakawa biotite granite and Ide diorite, both 2 cm in diameter and 4 cm in length.

2. Stress-strain results at high temperature

Stress-strain relations of granite and basalt were observed at high temperatures up to 800°C. Strain was measured with the wire resistance strain gage for high temperature at the temperature up to 600°C. Above 600°C, this "high temperature gage" were not applicable because of the increasing electrical conductivity of adhesive ceramic cement, which bind the gage with the specimen, and hence the strain was observed with the dial gage atached to the deforming piston at such temperature.

Fig. 1 shows the complete curves of stress-strain relation for Kitashirakawa granite at various temperature. Strain was observed both in the direction to which axial stress was applied and in the direction transverse to this axis up to the moment of the rupture. Then we will be able to estimate the mean Young's modulus, mean Poisson's ratio and accordingly the volume change at the every stage of deformation and fracture. In the previous paper,[3] we studied that the longitudinal strain is almost linear up to the rupture moment, while the lateral strain is rapidly increased with increasing stress, hence the volume of specimen will be expanded at the rupture stage. These anomalous volume change was also founded by Bridgman[1]. Now in this high temperature experiments, the behavior of deformation is quite the same. At higher temperature, the anomalous increasing of the lateral strain seems to be more intense. We also observed the consider-

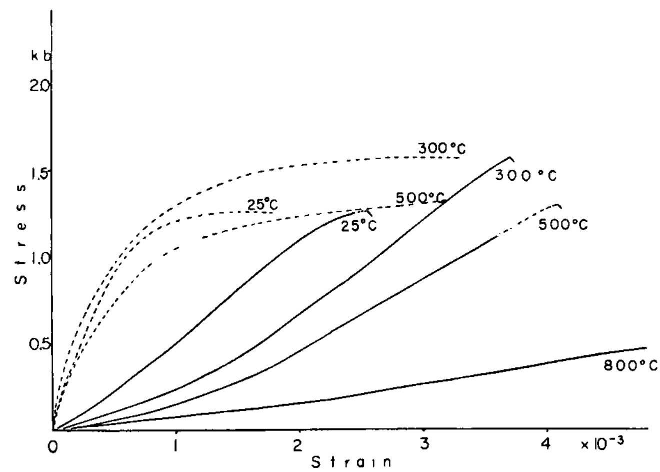

Fig. 1 Stress-strain results of Kitashirakawa biotite granite at various temperatures. Full lines denote the relations observed in the axial direction and dotted curves denote the relations in the direction transverse to the axial stress.

ably definite flow phenomena under relatively low stress. However we did not carried out such experiment to get the accurate observation.

We observed the variation of the figure of stress-strain results of same specimen, with increasing temperature. Fig. 2 and 3 illustrate such curves for Kitashirakawa granite and Yakuno basalt, respectively. The conclusion from these results will be summarized in the next paragraph.

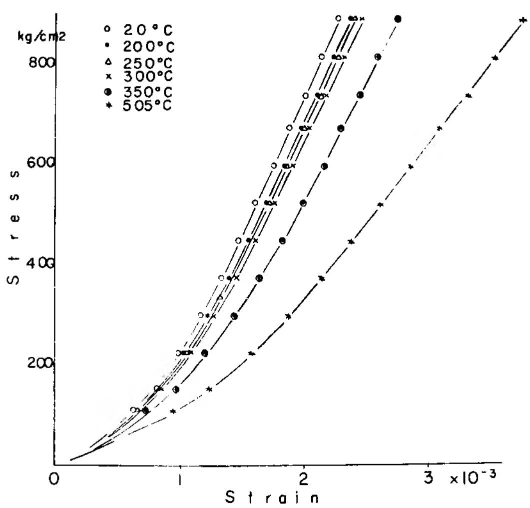

Fig. 2 Variation of stress-strain curve with increasing temperature for a test piece of Kitashirakawa biotite granite.

3. Variation of Young's modulus and strength with temperature

We see from Fig. 2, that the slopes of the stress-strain curves for Kitashirakawa granite are gradually flat with increasing temperature. This tendency become more obvious at the temperatures higher than 300°C. On the other hand, as we see from Fig. 3, the slopes of the curves at high temperature for Yakuno basalt do not become so different from that of the curve at room temperature.

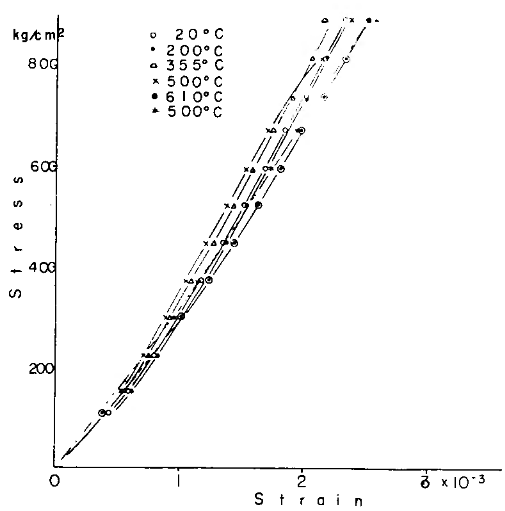

Fig. 3 Similar figure of Fig. 2 for a test piece of Yakuno olivine basalt.

We plotted the variation of mean Young's modulus with temperature for Kitashirakawa granite and Yakuno basalt in Fig. 4 and 5, respectively. To evaluate the mean Young's modulus, we took the stress interval ranging from 150 kg/cm² to 900 kg/cm². In this stress range, the stress-strain curves are almost linear. The value of Young's modulus of Kitashirakawa granite begins to decrease gradually at

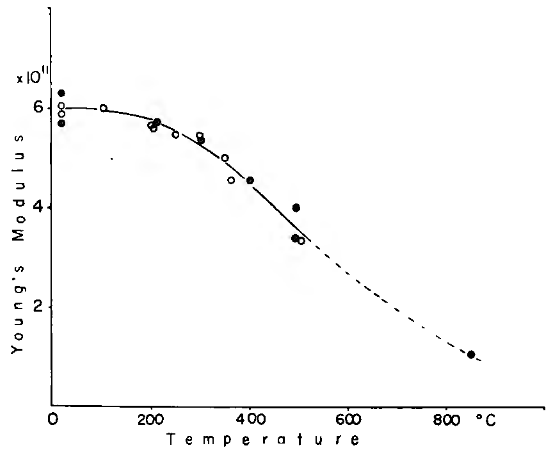

Fig. 4 Variation of mean Young's modulus with temperure for Kitashirakawa biotite granite.

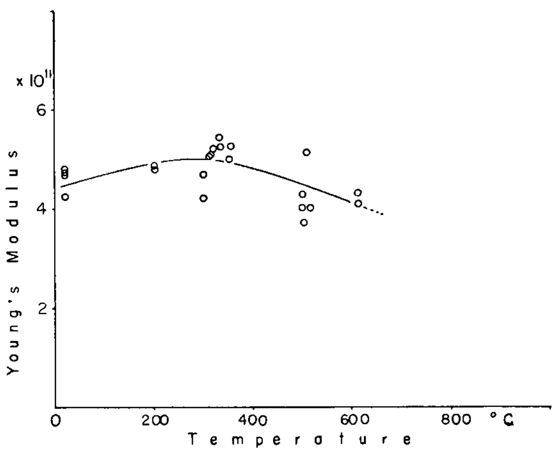

Fig. 5 Similar curve of Fig. 4 for Yakuno olivine basalt.

approximately 300°C, and the higher the temperature, the more rapidly it falls. On the other hand, as was already seen, the Young's modulus of Yakuno basalt does not vary with increasing temperature at least up to 600°C, but has approximately constant value.

Furthermore, we can evaluate from Fig. 1 the variation of strength of Kitashirakawa granite with temperature. Fig. 6 shows the strength of Kitashirakawa granite at various temperatures. The strength of granite decreases approximately linearly with elevated temperature. The point at which the strength-temperature curve crosses with abscissa (that is, the specimen has zero strength) will be the melting point of this specimen. The strength-temperature curve for Yakuno basalt is shown in Fig. 7. The strength of this basalt seems to be not so much decreased with elevated temperature, but have the maximum near about 500°C. However, the accumulation of the data will be not so sufficient as to acertain whether this inclination is plausible.

4. Stress-strain results at high temperature and pressure

Stress-strain relations were observed at high temperature up to 300°C under high confining pressure. We used silicon oil as the pressure transmitting medium, hence we could not elevate sufficiently high temperature, because such liquid has

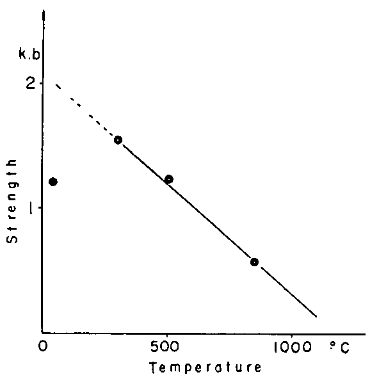

Fig. 6 Variation of crushing strength with increasing temperature for Kitashirakawa biotite granite.

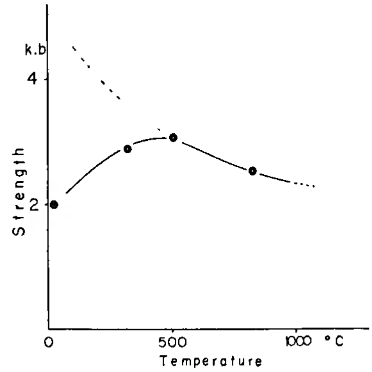

Fig. 7 Similar curve of Fig. 6 for Yakuno olivine basalt. Dotted extension illustrates the relation which will hold at high pressure and temperature.

low boiling temperature of about 300°C. If we carry out the experiment at more higher temperature under high pressure, we have to use the innert gas or ductile solid as the pressure medium. The experiments under such condition remain for future works.

The triaxial testing cylinder used at high temperature is shown in Fig. 8. Specimens were heated at the moderate temperature by the inner setting electric heater directly, so the temperature distribution in the specimen was not so uniform, that is, the temperature at the ending parts were a little lower than at the middle of the specimen, however, the its most part was kept within ±5°C during the full run. To keep the temperature constant and hold uniform over the specimen, was very difficult in such inner heating method. Outer heating method in which all the apparatus is contained in the furnace is much convenient to keep the condition uniformly. Griggs[2] used outer heating method at fairly high temperature. However, for the weakening of strength of the cylinder material, the outer heating method will be limitted at very high temperature.

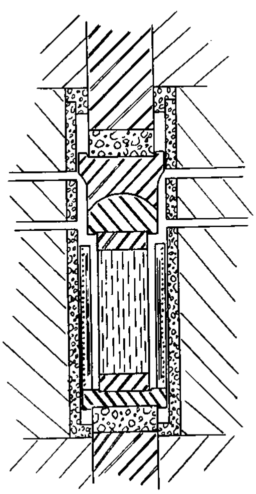

Fig. 8 Schematic representation of the experimental method of rock deformation at high pressure and temperature.

Strain was measured by the piston displacement method. This method is not quite suitable for measuring the strain of test piece which is contained in a high pressure cylinder, with sufficient accuracy. It is because of the fact that the effects of piston-distortion, deformation of the cylinder, friction resistance of gasket and so on, are very complicated to get the accurate correction. On the other hand, at the experiments at the room temperature, the wire resistance strain gage is very convenient, for using in the small container and it gives a considerably good value of strain even under high pressure condition. Unfortunately, at the elevated temperature above 250°C, we could not use this type of gage under high confining presstre, as it was very difficult to find out any adhesive of the electric insulating characteristics above such temperature so as to prevent the pressure transmitting oil penetrating into the specimen. Moreover, this temperature condition has the important role for the investigation of temperature effect of mechanical properties of rocks. Then the obtained stress-strain results are not so accurate to derive many definite conclusion from them.

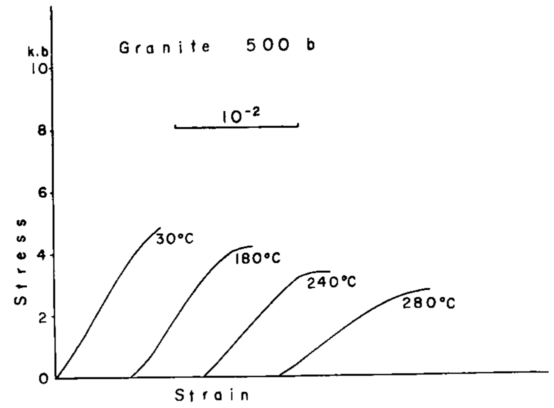

Fig. 9 Stress-strain results of Kitashirakawa biotite granite at various temperatures and 500 b. confining pressure.

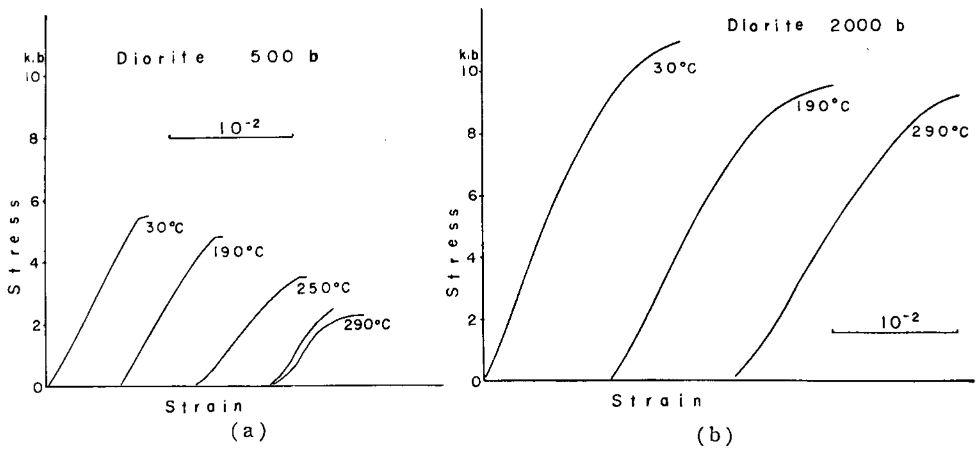

Fig. 10 Stress-strain results of Ide diorite at various high temperatures and (a) 500 b. and (b) 2,000 b. confining pressure.

Fig. 9 and Fig. 10 a, b) show the stress-strain curves at fixed confining pressure and varying temperature, for Kitashirakawa granite and Ide diorite, respectively. These figures illustrate that when the temperature becomes high, the curves are finished at lower stress and specimens are broken down. These also show the tendency that the slope of curve become flat with higher temperature, however, it will not be able to emphasize, because of the less accuracy of the obtained values of strain.

Fig. 11 and Fig. 12 show the stress-strain curves at constant temperature and various confining pressures, for Kitashirakawa granite and Ide diorite. In each

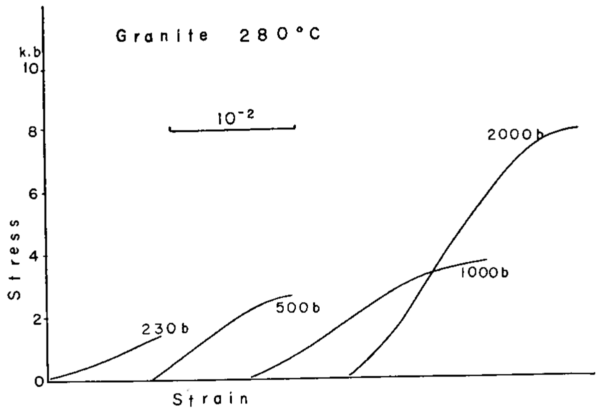

Fig. 11 Stress-strain results of Kitashirakawa biotite granite under various confining pressures, at 280°C.

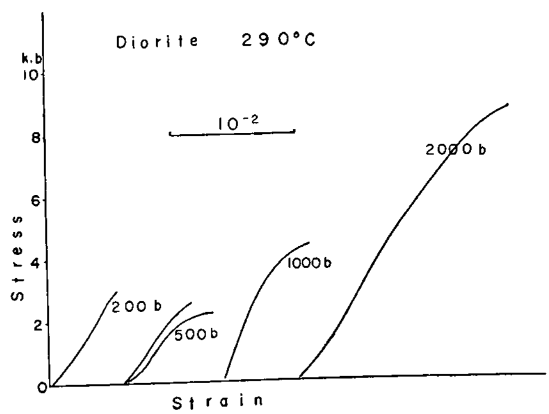

Fig. 12 Stress-strain results of Ide diorite under various confining pressures, at 290°C.

case, the curves are elongated to the higher stress and strain with higher pressure. This behavior is quite similar with that of the curves at room temperature under high confining pressure which was previously reported.

Acknowledgement

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